PILOT INJECTION BEHAVIOR AND ITS EFFECTS ON COMBUSTION IN A COMMON RAIL DIESEL ENGINE

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ABSTRACT

The influence of some injection parameters (main injection timing, pilot injection timing, pilot injection duration) on combustion, on noise and on vibration values of a Diesel engine has been evaluated performing experimental tests. The tests have been carried out using an in-line, four cylinders, and turbocharged FIAT 1929 cm3 TDI engine. The injection system of the engine used was the high-pressure Common Rail system. To measure combustion noise, two different piezoelectric accelerometers were mounted on the engine surface, on the top and on the side of the outer wall of the engine, close to the first cylinder. Moreover, the engine was equipped with a piezoelectric sensor for the measurement of the pressure in the combustion chamber. Experimental results were elaborated using an ANOVA (analysis of variance) technique, to evaluate the influence of the control parameters. The combustion pressures level and consequently the related vibrations and sound pressure level increase with the increase of the main injection advance. The ignition delay increases at the increasing of crank angle before TDC at which main injection occurs; the fuel quantity in ignition delay is increased too, then the peak of heat release increases with the increasing of the injection advance. During idling, the mean values of noise and vibration RMS tend to increase with the increase of the duration of the energizing current for the pilot injection; an opposite behavior is showed for the other tests conditions, when the measured signals show an opposite behavior. Regarding the timing of the pilot injection, it can be noted that the pilot timing exerts a clear influence on noise level only for idling conditions; while for the other tests the influence is less meaningful. For some tests conditions, the pilot timing does not have as a significant effect on the ignition delay of the main injection. The analysis of variance show that the main injection timing and the energizing time of the pilot injection appear to be the most meaningful parameters, as previously seen, for the noise and the vibration level. The influence of the pilot injection timing is less meaningful.

KEYWORDS

Automotive control, Energy control, Engine control, Fuel control injection, Noise control, Power control.

1. INTRODUCTION

The Common Rail fuel injection system, for passenger car DI Diesel Engines, allows to choose freely injection pressure, fuel quantity, timing of injection: these new possibilities contribute to further improvements of DI engines concerning noise, exhaust emissions and engine torque. In the Common Rail system, the solenoid valve, used to control the injector, can be energized several times during one working cycle of the engine: in this way multiple injection, pilot injection and post injection are feasible.

A precise control of the pilot injection will reduce the combustion noise and the particulate emission (Stumpp and Ricco, 1996). Some Authors (Dürnholtz, *et al.*, 1994) outlined and described the potential improvements in combustion and exhaust emissions characteristics using injection rate shaping and pilot fuel injection. These improvements have been analyzed for many applications using a prototype injection system with advanced hydraulic performances. Furthermore, it has been shown how pilot injection should be performed in order to get a reduction of both exhaust emissions and combustion noise. Finally, the potential for optimizing engine behavior, modifying these injection system characteristics, has been discussed.

Emissions and performance studies were carried out to explore the effects of EGR and multiple injections on particulate, NOx, and fuel consumption (Pierpoint, *et al.*, 1995). A heavy-duty Diesel engine was used to develop an understanding of rate-shaped and split injections influences on soot and NOx emissions (Nehmer and Reitz, 1994). Tabuchi, *et al.* (1995) have reported progress in fuel injection technology including the analysis of injection pressure pattern, injection rate pattern, and injection timing and spray pattern.

Tennison and Reitz (2001) conducted an investigation of the effects of injection parameters on emissions and performance in an automotive Diesel engine. Increasing the injection pressure reduced the smoke emissions, with no penalty in oxides of nitrogen (NOx) or brake specific fuel consumption (BFSC). The effect of the start of injection of the pilot was found to be small compared to changes resulting from varying the main injection timing; the effect of pilot injection on smoke, NOx, BSFC, unburned hydrocarbons was discussed. Endo, *et al.* (1997) showed that optimizing pilot injection enables engine idling noise and vibration to reduce as well as NOx emissions. In the work of Badami, *et al.* (1999) the influence of injection pressure on the performance of a passenger car Diesel engine prototype equipped with a Common Rail Fuel Injection System has been investigated. The results from the experimental diagnosis of the combustion process taking place in a single cylinder D.I. Diesel engine with common rail system were presented and analyzed in a paper of Lapuerta, *et al.* (1999).

Simulation codes were developed and revised to study injection characteristics and to investigate the behavior of the injector control valve, with the aim to predict the operation conditions of the injection system when pilot injection is performed, and to investigate some instabilities, related to the control of the fuel injected during the main injection, or to the time delay between pilot and main injection (Ficarella, *et al.*, 1999).

In the present study, the influences of main injection timing, pilot injection timing and duration, on engine combustion and noise, were evaluated. Experimental results were elaborated using an ANOVA (analysis of variance) technique, to evaluate the influence of the control parameters.

2. EXPERIMENTAL SETUP AND TEST CONDITIONS

A 2-liter, 4-cylinder, direct injection Diesel engine (FIAT 1929 cc TDID type 154 D1.000) was used for the experiments (Fig. 1). It was equipped with a GARRETT TD 2502 turbocharger and an intercooler; a Common Rail fuel injection system (BOSCH 1350 bar) was used. A bore of 82.6 mm and a stroke of 90 mm characterized the engine. An Electronic Control Unit (ECU), connected to a PC, controlled the Common Rail system; running the supervision software, values of several injection parameters were set up. The details of the test bench used for the present research can be found in Carlucci, *et al.* (2001a; 2001b).

During the tests, noise emissions were measured using an ambient microphone; a Synponie GRAS 41 AL measurement system was used, with a 40 AR microphone. The microphone was located at 0.5 m from the side base of the engine, on the opposite side with respect to the exhaust and turbocharger system, and 1 m above the floor. The microphone measurements were processed and stored in a PC; the equivalent sound pressure level L_{eq}, A-weighted, for an integration time of 20 ms, was calculated.

Two piezoelectric accelerometers (KYSTLER K-SHEAR Piezotron Accelerometers type 8704B100) were mounted firmly on the engine surface, using an adhesive (mounting) pad. The first one was mounted on the side of the outer wall of the engine, close to the first cylinder (in the continuation it will refers to the relative data as DATA1); the second one was mounted on the top of the engine (in the continuation DATA2), on the bolt that clamps the head of the cylinder to the crankcase. Both the accelerometers were mounted with a vertical orientation; the sensor sensitivity was 50 mV/g (range ±100 g). Single channel couplers powered the accelerometers. The accelerometers signals, with the signal of the energizing current of the injector, were simultaneously digitized using an analog/digital acquisition board (NATIONAL INSTRUMENTS) on a PC. RMS of the signals was calculated.

Measurement error for equivalent sound pressure level has been evaluated equal to 0.1 dB. Error for the frequency response 0.6-9 kHz of the accelerometer is in the range ±5%, while the transverse sensitivity is 1.5%. Measurement error in the analog/digital data conversion and acquisition has been evaluated equal to 0.3%.

Three different series of experimental tests were performed, for different values of injected fuel quantity (Qc) and engine torque (Table 1A), from idling to 2000 rpm. For each series, three different injection parameters were varied, according to Table 1B: main injection timing (Ai), actuated injection timing of pilot injection (jAiP), energizing time (injection duration) of pilot injection (jETP1). Injection pressure was set at 90 MPa. Engine speed and water temperature were monitored: data were collected only after the engine had reached a steady-state operating condition. In Tab. 1C test condition for the cases showed in the following figures are summarized.

Table 1A – Experiments series

Experiment series	**Qc fuel quantity to be injected (mm^3/cycle)**	**Torque (load)**	**Speed (average RPM)**
SERIES 1	17	Idle	850
SERIES 2	24	77%	1200
SERIES 3	31	100%	2000

Table 1B – Experiments parameters

PARAMETER	**VALUES**	**UNITS**
Ai main injection timing	0 – 5 – 10	Degree crank angle before top dead center (DCABTDC)
jAiP actuated injection timing of the pilot injection	10 – 35 – 60 NOTE: 10 CA only for Ai=0 CA	Degree crank angle before top dead center (DCABTDC)
jETP1 energizing time (injection duration) of the pilot injection	50 – 150 – 250 NOTE: 50 ms corresponds to an injection with no pilot one	μs

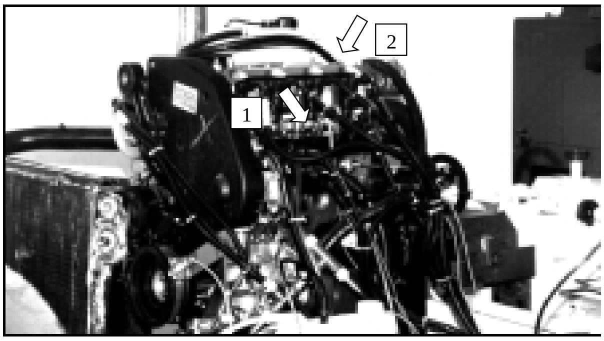

Fig. 1: Test bench and sensors position.

3. ANALYSIS OF THE RECORDED SIGNALS

The powertrain is a primary contributor to high frequency noise in an automobile; several engine subsystems contribute to sound pressure, as intake manifold, heads, block, oil pan (Kaminsky and Ungleniecs, 1997). Some Authors (Kohketsu, *et al.*, 1994) showed that in all operating ranges of a direct injection type Diesel engine, sound pressure levels (SPL) has its peak within the range of 1 to 2 kHz; moreover, the research showed, in all engine operating ranges, a good correlation between the 1 kHz value of the cylinder pressure level and the overall value of the engine noise; since the combustion noise can be evaluated in terms of frequency-analyzed cylinder pressure level, combustion noise can be correlated to overall engine noise.

Combustion noise, one of the components of the engine noise, is attributable to the cylinder pressure generated during combustion. Cylinder pressure acts as an exciting force, and is transmitted and attenuated as it goes through all the parts that constitute the engine; radiated as sound from the cylinder head, crankcase, etc., it turns into combustion noise. Engine vibrations are due to combustion and piston slap. Mechanically induced excitation in the engine is generated by piston slap, timing gear impact, bearing impact, fuel system, valve system and accessories. Piston slap is considered to be one of the most important sources of mechanical noise in Diesel engines (Villaroel and Agren, 1997). Piston slap occurs when the traveling piston bounces from one side of the cylinder wall to the other.

For each value of the injected fuel (Table 1A), the three controlling parameters were varied according to the values listed in Table 1B, and then 27 tests for each fuel-injected quantity were performed.

Response of the engine depends on the controlling parameters previously seen (Ai, jAiP, jETP1); during the experimental tests, each parameter can varies being equal to some discrete values, as detailed in

Table 1B; the values of the three parameters are named, respectively, A_i, B_j, C_k, with i=1...a, j=1...b, and k=1...c; for the case under investigation, a=b=c=3, while, i.e., A_1=0 (first value of the parameter Ai).

Defining y_{ijk} as the generic measured engine response (sound pressure level L_{eq} or RMS of vibrations), obtained during a test with the controlling parameters set to the values A_i, B_j and C_k, the mean value of all measurements can be calculated as:

$$\overline{y}_{***} = \frac{1}{n_{***}} \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{c} y_{ijk} \qquad (1)$$

Where *a*, *b*, and *c* are, respectively, the number of the values that the aforesaid parameters can assume (in the case in examination all equal to 3), and n_{***} is the number of all measurements; moreover:

$$\overline{y}_{i**} = \frac{1}{n_{i**}} \sum_{j=1}^{b} \sum_{k=1}^{c} y_{ijk} \qquad (2)$$

Where $\overline{y}_{i**}$ is the mean value of the n_{i**} measurements characterized by the first parameter set to the value A_i. Similarly, the other means values $\overline{y}_{*j*}$ and $\overline{y}_{**k}$ can be defined.

The details of the experimental data processing are can be found in in Carlucci, *et al.* (2001a; 2001b).

In Figs. 2-4-6 are reported the effects of energizing time (injection duration) of pilot injection (jETP1), main injection timing (Ai), and actuated injection timing of pilot injection (jAiP), on sound pressure level (L_{eq}) and RMS of engine vibrations. The showed values are the mean values for the measurements, as defined in Eq. (2); the measured values are normalized between 0 and 100%.

Table 1C – Figures references

	SERIES (Tab. 1A)	**Ai (DCA BTDC)**	**jAiP (DCA BTDC)**	**jETP1 (μs)**
1715**35	1	Variable	35	150
2425**35	2	Variable	35	250
2415**45	2	Variable	45	150
17**0525	1	5	25	Variable
17**0545	1	5	45	Variable
24**0035	2	0	35	Variable
24**0545	2	5	45	Variable
171505**	1	5	Variable	150
242505**	2	5	Variable	250
172505**	1	5	Variable	250

4. EFFECTS OF THE TIMING OF THE MAIN INJECTION

Figs. 2A, 2B and 2C show that the timing of main injection, expressed as crank degrees before TDC for the beginning of the injector energizing, strongly influences noise emissions, as defined in Eq. (2). RMS of the vibrations, measured by the accelerometers, increases with the delay of the injector energizing, for idling and 50% torque tests. For injected fuel equal to 31 mm^3/cycle, the trend of the accelerometers signals show a variation only for crank degrees larger than 5 DBTDC, while it tends to be constant for smaller crank degrees. The trends of the three measured signals (ambient noise and vibrations measured at the two locations) are in agreement for the three signals, although the range of variation of the ambient noise is less meaningful of the range of variation of the vibrations.

Other Authors (Kohketsu, *et al.*, 1994) proved the same behavior at idling range, when the combustion pressure level (CPL) at 1 kHz (related to the sound pressure level as previously discussed) decreases with injection timing delay (increasing of the crank angle before TDC. For other test conditions, the results obtained by Kohketsu, *et al.* (1994) show a different behavior, although the CPL appears to be less sensitive to variations of the injection timing, especially for the high-pressure injection system, as it is the one used for the present study.

Fig. 3A show the effects of timing of main injection on the peak value of the pressure derivative during the combustion cycle, for series 1 and 2 data. As it can be seen, for the cases under analysis (idling and 77% max. torque at 1200 rpm), there was an increase of the peak values of pressure derivative with the increase of main injection advance. This behavior is consistent with the increase of noise and vibration levels, since combustion noise is attributable to the cylinder pressure generated during combustion, and the mechanically induced excitation in the engine is related to pressure derivative.

Fig. 3B show, as an example, pressure derivative curves for an engine speed of 1200 rev/min and a total mass injected of 24 mg/inj., for different main injection timing (see Tab. 1C for tests conditions). As it can be seen, there was an increase in the peak values of pressure derivative, with the main injection advance: moreover, also ignition delay tends to increase with the main injection advance, because the time corresponding to the peak value of the derivative tends to come with a smaller advance respect to the increase of injection advance. The same behavior was showed by other tests.

The combustion pressure level and consequently the related sound pressure level increase with the increase of the premixed combustion phase. The relationship between CPL and injection timing depends on the ignition delay period, and on the crank angle at which ignition occurs. Kohketsu, *et al.* (1994) proved that the shorter the ignition delay, the less the premixed combustion phase and the CPL; at idling condition, while ignition occurs before TDC, the ignition delay is increased at the increasing of crank angle before TDC (CABTDC) at which injection occurs; the fuel quantity in ignition delay is increased too, then the peak of heat release increases with the increasing of the injection advance: the overall effect is an increase of CPL and SPL. For the other test conditions, the experimental results reported by Kohketsu, *et al.* (1994) showed a different behavior, because the ignition occurs after TDC; when the value of the CABTCD at which injection occurs is increased (reduction of the injection delay), the ignition delay and the fuel quantity in ignition delay phase decrease; then, the peak value of heat release tends to decrease too: as a result CPL reduces with the increase of the injection advance. For the Common Rail injection pressure used, the high pressure of injection and, then, the better atomization can produce a shorter combustion period, so that not only at the idling, but also at other test conditions the combustion behavior is similar to idling test of Kohketsu, *et al.* (1994).

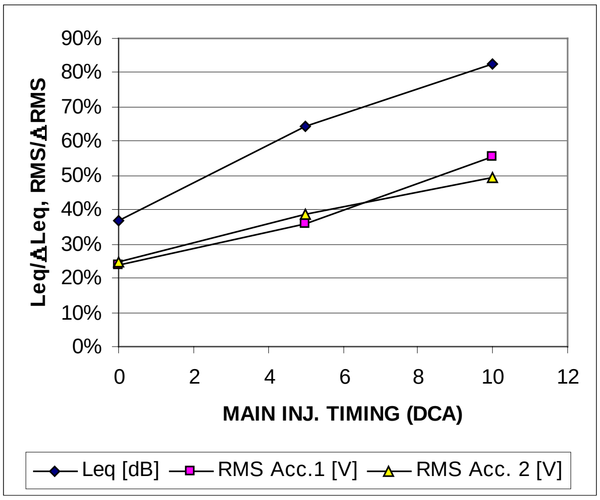

Fig. 2A: Effect of main injection timing (Ai) on sound pressure level and RMS of vibrations – series 1 tests (Tab. 1A)

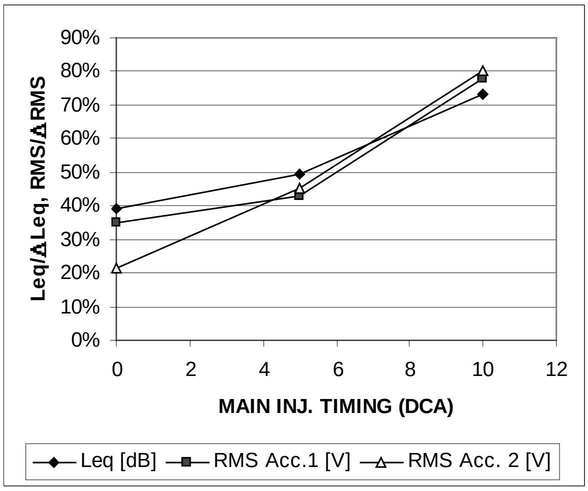

Fig. 2B: Effect of main injection timing (Ai) on sound pressure level and RMS of vibrations – series 2 tests (Tab. 1A)

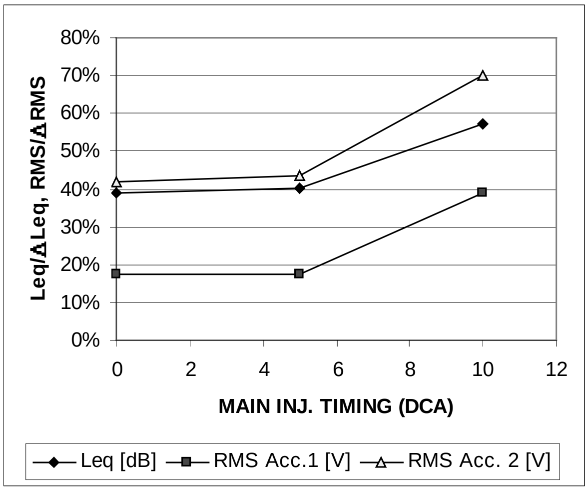

Fig. 2C: Effect of main injection timing (Ai) on sound pressure level and RMS of vibrations – series 3 tests (Tab. 1A)

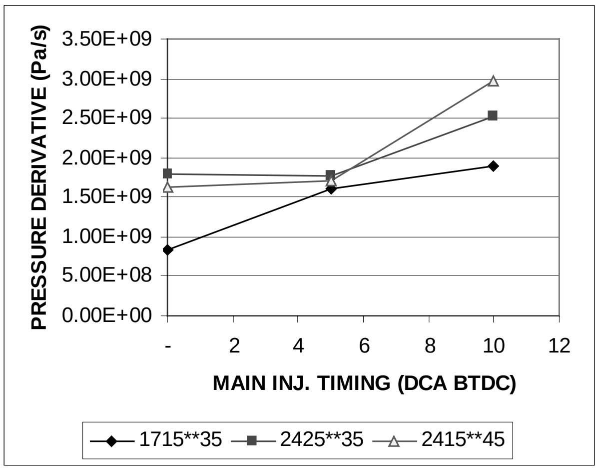

Fig. 3A: Effects of main injection timing on peak values of pressure derivative (see Tab. 1C for curves references)

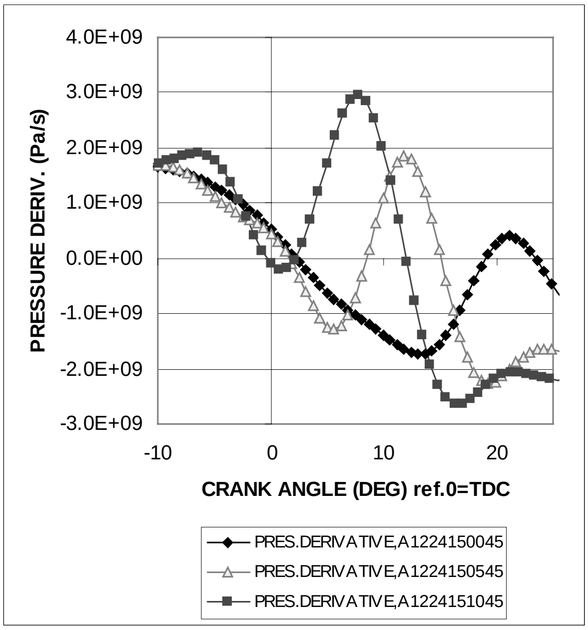

Fig. 3B: Pressure derivative for series 2, jAiP=45 DCABTDC, jETP1= 150 µs, main injection timing Ai=0 DCABTDC (curve A1224150045), 5 DCABTDC (curve A1224150545), 10 DCABTDC (curve A1224151045)

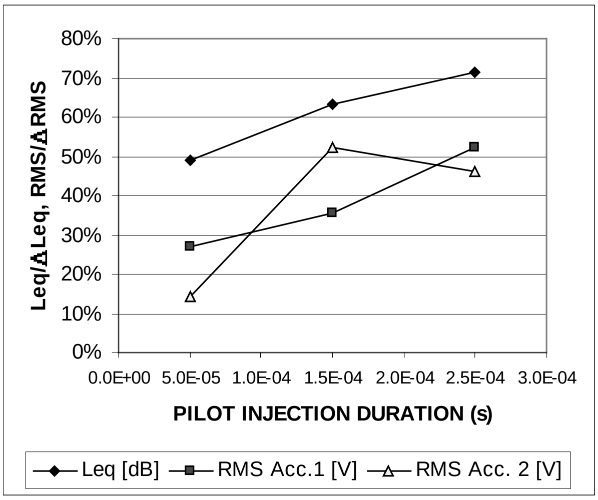

Fig. 4A: Effect of energizing time of the pilot injection (jETP1) on sound pressure level and RMS of vibrations – series 1 tests (Tab. 1A)

5. EFFECTS OF THE DURATION OF THE PILOT INJECTION

Research has shown that pilot injection can affect combustion noise significantly (Tennison and Reitz, 2001).

During idling, the noise and vibrations (expressed as RMS) tend to increase with the increase of the duration of the energizing current for the pilot injection (Fig. 4A). An opposite behavior is showed for injected fuel equal to 24 mm^3/cycle (Fig. 4B); it can be observed that the variations of the three parameters (ambient noise and vibration level for location 1 and 2) are in agreement, although the range of variation of the ambient noise is still less meaningful, as previously seen. For serie 3 tests, ambient noise and vibrations measured at location 2 (at the top of the engine) are in agreement, decreasing with the increase of the pilot injection duration, while the vibrations measured at the side of the engine, show an opposite behavior.

Stumpp and Ricco (1996) reported that a small injection quantity of 1-2 mm^2/stroke before the main injection is suitable to reduce the combustion noise, while a too small and too early pilot injection increases the combustion noise. The fuel injected during the pilot injections depends on the injection pressure and on the pilot injection duration; for the present study, while injection pressure was kept almost constant for all the tests (and equal to 90 MPa), the fuel injected during the pilot injection was varied up to 5.6 mm^2/stroke (for Qc=31 mm^3/stroke), and its effects on SPL is different for the different engine conditions. Dürnholz, *et al.* (1994) showed a decrease of noise with the pilot fuel amount, at 2000 rpm and medium load: the main reason for the reduction of noise, for medium and high load, was the decrease of ignition delay due to high temperature level at the start of the main injection.

Fig. 5A shows the apparent net heat release profiles for different pilot injection duration (from single injection to 250 µs for pilot duration), for an engine speed of 850 rev/min and a total mass injected of 17 mg/inj.(see Tab. 1C for tests conditions). As can be seen from the figure, the pilot injection produces a slightly lower values of the peak heat release, and a slightly decrease in the ignition delay of the main injection, as other researcher have also found (Tennison and Reitz, 2001). Also Endo, *et al.* (1997) found that increasing the pilot injection fuel quantity, the ignition delay of main injection is shortened, and then premixed combustion is restrained by combustion of pilot injection.

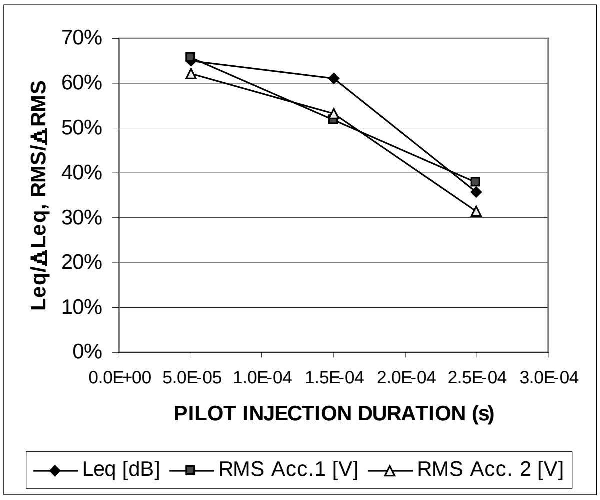

Fig. 4B: Effect of energizing time of the pilot injection (jETP1) on sound pressure level and RMS of vibrations – series 2 test (Tab. 1A).

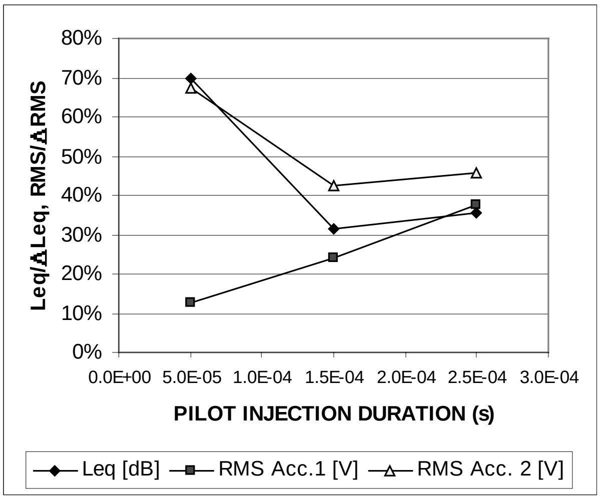

Fig. 4C: Effect of energizing of the pilot injection (jETP1) on sound pressure level and RMS of vibrations – series 3 tests (Tab. 1A)

Fig. 5B shows peak values of pressure derivative, during the combustion cycle, vs. pilot injection duration (see Tab. 1C for tests conditions). For series 1 tests, there was an increase of the peak values of pressure derivative, at the higher pilot inj. duration, up to 150 µs; the result is consistent with the increase of noise and vibrations levels (Fig. 4A); for higher pilot inj. duration, the pressure derivative tends to increase for series 2 test, while tends to reduce for series 1 tests.

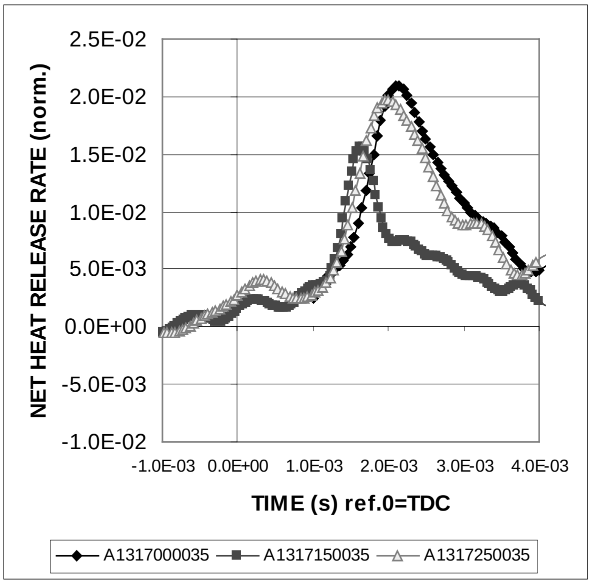

Fig. 5A: Apparent net heat release rate, for series 1, Ai=0 DCABTDC, jAiP=35 DCABTDC, pilot inj. duration jETP1=0 µs (curve A1317000035), 150 µs (curve A1317150035), 250 µs (curve A1317250035)

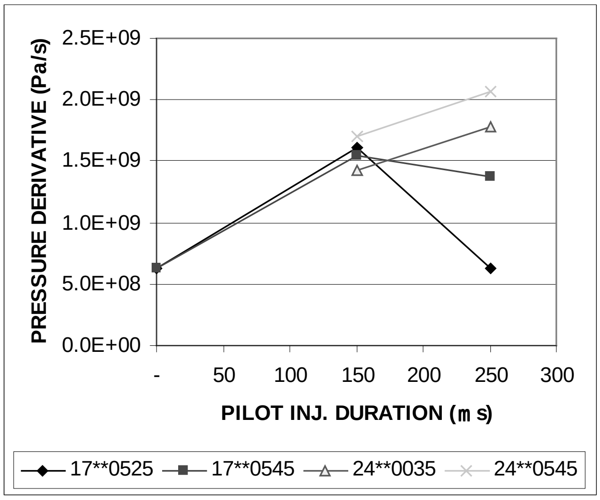

Fig. 5B: Effects of pilot injection duration on peak values of pressure derivative (see Tab. 1C for curves references)

6. EFFECTS OF THE TIMING OF THE PILOT INJECTION

The influence of the timing of the pilot injection current is showed in Fig. 6A, 6B and 6C. It can be noted that the pilot timing exerts a clear influence on noise level only for idling conditions, while for the other tests the influence is less meaningful. It has to be taken into account that the range of variation of the pilot timing is large. Moreover, for the earlier timing of the pilot injection, the combustion of the pilot fuel is completed when the main injection occurs, while for the later pilot injection timing, the pilot fuel is still burning at the main injection. Other Authors (Erlach, *et al.*, 1995) reported that the optimum point that characterizes the influence of the pilot timing on NOx and smoke is when the pilot fuel combustion is nearly completed at the main injection start. Moreover, the engine behavior for earlier timing is quite similar for later timing.

The effect of the pilot injection timing was studied for the condition at 850 rev/min (series 1); in this case, the pilot timing was varied in 10 CA° increments while holding the main injection timing constant. The results are showed in Fig. 7A; the figure shows that the pilot timing does not have as a significant effect on the ignition delay of the main injection, as other researchers have also found (Tennison and Reitz, 2001).

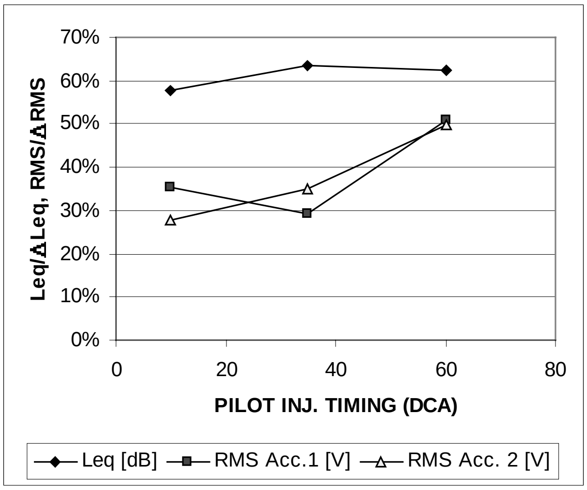

Fig. 6A: Effect of actuated injection timing of the pilot injection (jAiP) on sound pressure level and RMS of vibrations – series 1 tests (Tab. 1A)

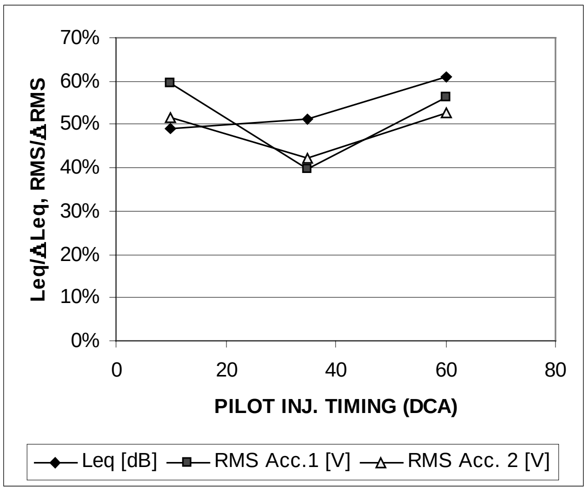

Fig. 6B: Effect of actuated injection timing of the pilot injection (jAiP) on sound pressure level and RMS of vibrations – series 2 tests (Tab. 1A).

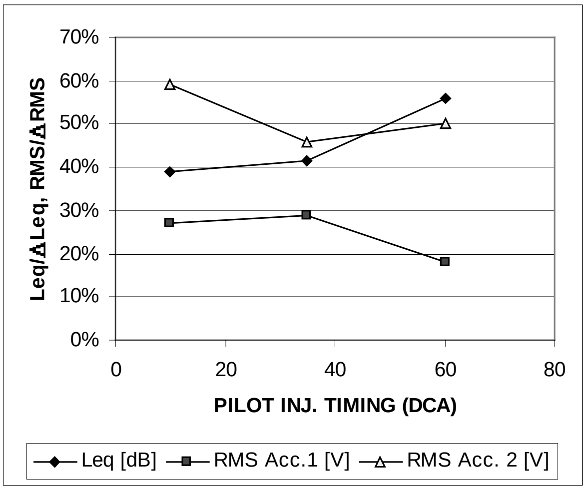

Fig. 6C: Effect of actuated injection timing of the pilot injection (jAiP) on sound pressure level and RMS of vibrations – series 3 tests (Tab. 1A)

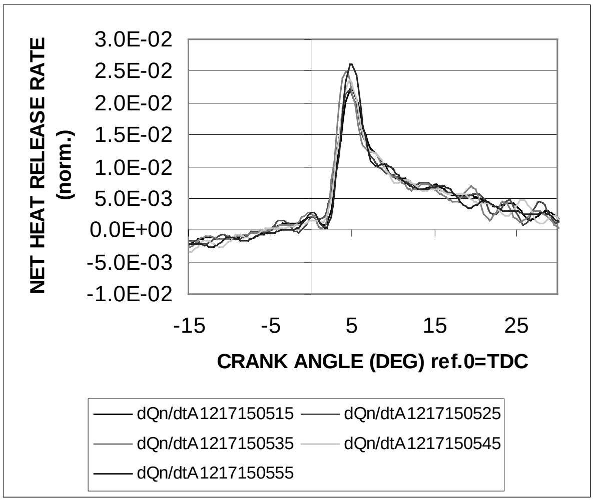

Fig. 7A: Apparent net heat release rate, for series 1, Ai=5 DCABTDC, jETP1=150 μs, pilot inj. timing jAiP=15 DCABTDC (curve A1217150515), 25 DCABTDC (curve A1217150525), 35 DCABTDC (curve A1217150535), 45 DCABTDC (curve A1217150545), 55 DCABTDC (curve A1217150555)

Fig. 7B shows net apparent heat release for different advanced pilot timing, from single injection test to pilot-main injection test with a pilot advance of 55 DCABTDC. The comparison of the curve with no pilot injection (test A1224150515), with the curve with a pilot advance of 25 DCA (test A1224150525), shows a diminished peak heat release of the main injection and a noticeable reduction of the ignition delay of the main injection; as the pilot injection timing is further advanced, the heat release rate of the main injection is increased, and consistently also the ignition delay. The same behavior was found by others researchers (Tennison and Reitz, 2001); in fact, increasing the pilot advance, the pilot burn effectively tends to disappear, because the fuel-air mixture could in fact be overmixed and too lean to burn for the very advanced pilot injection timing; consequently, the peak heat release tends to increase.

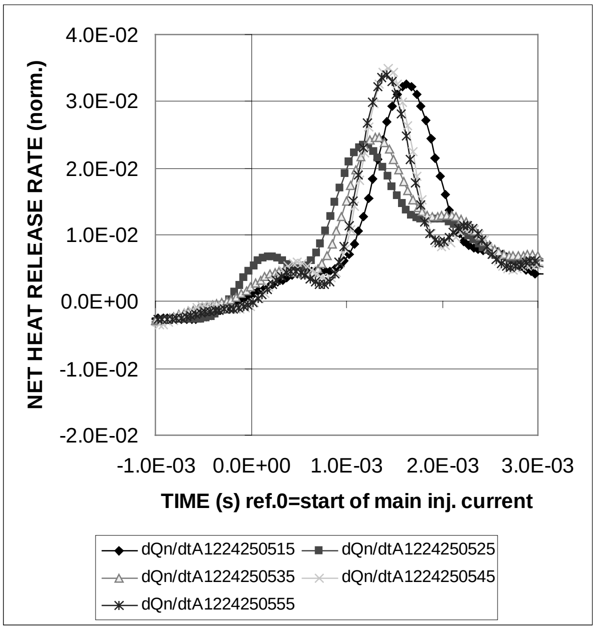

Fig. 7B: Apparent net heat release rate, for series 2, Ai=5 DCABTDC, jETP1=250 µs, no pilot inj. (curve A1224150515), pilot inj. timing jAiP=25 DCABTDC (curve A1224150525), 35 DCABTDC (curve A1224150535), 45 DCABTDC (curve A1224150545), 55 DCABTDC (curve A1224150555)

7. ANALYSIS OF EXPERIMENTAL TESTS USING THE ANALYSIS OF VARIANCE (ANOVA)

Supposing that the response of the engine system depends on the injection parameters previously seen (Ai, jAiP, jETP1), it is possible to consider a model were the following equation is used to predict the response of the system (Bernard, *et al.*, 1990):

$$\mu_{ijk} = p_{ijk} + p_{i**} + p_{*j*} + p_{**k} \qquad (3)$$

Where the parameters *p* are calculated as follows:

$$p_{***} = \bar{y}_{***} \qquad (4)$$

$$p_{i**} = \bar{y}_{i**} - p_{***} \qquad (5)$$

Parameter p_{*j*} and p_{**k} can be evaluated in the same way. The model errors (residuals) can be evaluated as:

$$d_{ijk} = \mu_{ijk} - y_{ijk} \qquad (6)$$

The parameters sum of squares are defined as:

$$s_A^2 = \frac{\left[\frac{n_{***}}{a} \sum_{i=1}^{a} p_{i**}^2 \right]}{\upsilon_A} \qquad (7)$$

$$\upsilon_A = a - 1 \qquad (8)$$

Where ν_A is the degrees of freedom for the parameter A; ν_B and ν_C can be evaluated in a similar way; moreover:

$$s_R^2 = \frac{\left[\sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{c} d_{ijk}^2 \right]}{\upsilon_R} \qquad (9)$$

$$\upsilon_R = n_{***} - 1 - (a-1) - (b-1) - (c-1) \qquad (10)$$

It has to be pointed out that in the model described in Eq. (3), the values of p_{i**}, p_{i**}, and p_{i**}, can vary freely, without no particular hypothesis that the effect of the controlling parameters is linear.

It is possible to compute Fisher's test to evaluate the level of significance of the parameters, considering the ratio s^2_A/s^2_R and the degree of freedom ν_A and ν_R for each parameter. The results are summarized in Table 2A, 2B and 2C.

The tables show that the main injection timing and the energizing time of the pilot injection appear as the most meaningful controlling parameters, as previously seen, of the ambient noise and the combustion vibrations; on the contrary, the influence of the pilot injection timing is characterized by a low value of significance. Moreover, the level of significance of the parameter tends to reduce for higher quantities of injected fuel.

Table 2A – Significance level for L_{eq}

PARAMETER	Fuel = 17 mm^3/cycle	Fuel = 24 mm^3/cycle	Fuel = 31 mm^3/cycle
jETP1 energizing time of the pilot injection	97.83%	99.97%	99.61%
Ai main injection timing	99.998%	99.99%	78.81%
jAiP injection timing of the pilot injection	27.96%	82.57%	72.11%

Table 2B – Significance level for accelerometer 1

PARAMETER	Fuel = 17 mm^3/cycle	Fuel = 24 mm^3/cycle	Fuel = 31 mm^3/cycle
jETP1 energizing time of the pilot injection	94.18%	98.56%	98.61%
Ai main injection timing	98.51%	99.98%	98.58%
jAiP injection timing of the pilot injection	89.03%	93.21%	66.28%

Table 2C – Significance level for accelerometer 2

PARAMETER	Fuel = 17 mm^3/cycle	Fuel = 24 mm^3/cycle	Fuel = 31 mm^3/cycle
jETP1 energizing time of the pilot injection	99.97%	96.64%	97.20%
Ai main injection timing	97.63%	99.99%	99.08%
jAiP injection timing of the pilot injection	95.95%	40.59%	64.96%

8. CONCLUSION

The influence of main injection timing, pilot injection timing and duration, on engine combustion and noise, was evaluated. Furthermore, the experimental data were analyzed using the ANalysis Of VAriance (ANOVA).

The RMS of the accelerometer signal, located on the side and on the top of the engine, increases with the main injection advance; for higher values of injected fuel, the increase is less evident for small injection advance (less than 5 DCABTDC). The noise level measured by the microphone shows a quite similar behavior. The combustion pressure level and consequently the related sound pressure level increase with the increase of the premixed combustion phase. The ignition delay increases at the increasing of crank angle before TDC (CABTDC) at which main injection occurs (the nearer to TDC, the better the ignition conditions, and the shorter the ignition delay); the fuel quantity in ignition delay is increased too, then the peak of heat release increases with the increasing of the injection advance: the overall effect is an increase of CPL and SPL. For the Common Rail injection pressure used, the high pressure of injection and, then the better atomization can produce a shorter combustion period, so that not only at the idling, but also at other test conditions the combustion behavior is similar to idling test. The detailed analysis of the combustion pressure shows consistent results; the peak value of the pressure derivative tends to increase with the main injection advance.

During idling, the mean values of noise and vibration RMS tend to increase with the increase of the duration of the energizing current for the pilot injection; an opposite behavior is showed for the other tests conditions, when the measured signals show an opposite behavior. As can be seen from the analysis of combustion pressure and heat release profiles, the pilot injection produces a lower values of the peak heat release, and a decrease in the ignition delay of the main injection: increasing the pilot injection fuel quantity, the ignition delay of main injection is shortened, and then premixed combustion is restrained by combustion of pilot injection.

Regarding the timing of the pilot injection, it can be noted that the pilot timing exerts a clear influence on noise level only for idling conditions; while for the other tests the influence is less meaningful. For some tests conditions, the pilot timing does not have as a significant effect on the ignition delay of the main injection. Other tests showed a diminished peak heat release of the main injection and a noticeable reduction of the ignition delay of the main injection; as the pilot injection timing is further advanced, the heat release rate of the main injection is increased, and consistently also the ignition delay. Increasing the pilot advance, the pilot burn effectively tends to disappear, because the fuel-air mixture could in fact be overmixed and too lean to burn for the very advanced pilot injection timing; consequently, the peak heat release tends to increase.

The analysis of variance show that the main injection timing and the energizing time of the pilot injection appear to be the most meaningful parameters, as previously seen, for the noise and the vibration level. The influence of the pilot injection timing is less meaningful.

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